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UNITED STATES MARINE CORPS AERIAL REFUELING REQUIREMENTS ANALYSIS

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ABSTRACT

The United States Marine Corps (USMC) currently operates a fleet of KC130 aerial refueling tanker aircraft. This paper uses queuing and simulation models to examine the USMC KC130 tanker requirement, contrasts the results and explores the budgetary implications of alternative fleet requirements. This analysis finds that queuing models don't account for some of the complexities of aerial refueling operations. Therefore, queuing models may miscalculate the KC130 requirement. Simulation models give a more accurate depiction of actual KC130 requirement. Further, by incorrectly specifying the requirement the USMC could be faced with significant operational and budgetary implications.

1 INTRODUCTION

The United States Marine Corps (USMC) currently operates a mixed fleet of KC130 aerial tanking aircraft, including series F, R, and T. The F and R aircraft are approximately 30 years old. The USMC is beginning to retire these models in favor of new J series aircraft. As the USMC begins replacing its aging fleet with a newer, more capable model, it is natural to re-estimate the USMC KC130 requirement. This paper uses both queuing theory and simulation to examine the USMC KC130J fixed-wing aerial refueling requirement. This paper contrasts these methodologies and explores the budgetary implications of alternative fleet requirements.

2 AERIAL REFUELING BACKGROUND

The KC130 requirement assumes that the USMC retains sufficient KC130 capacity to meet USMC organic refueling requirements during two nearly simultaneous major theater wars (2MTW). The 2MTW scenario envisions nearly simultaneous confrontations in both western and eastern theaters. Defense planning projects the aircraft deployed in each theater, by week. The KC130 requirement is calculated for the week when the combined demand for KC130 services is the greatest across both theaters.

The USMC refueling capable fixed-wing aircraft include: F/A-18A/C/D, EA-6B, and AV-8B. The CH-53E helicopter is also a refueling capable USMC aircraft, but the helicopter KC130 requirement is independent of the fixed-wing requirement due to operational policies and technical characteristics of the refueling drogues. (The USMC KC130 uses a probe and drogue refueling system. The KC130 trails a hose from each wing, with a basket (refueling drogue) attached to the end of each hose. Receiver aircraft are equipped with refueling probes. When the probe engages the drogue, gas is passed from the KC130 tanker to the receiver aircraft.) The remainder of this paper compares alternative procedures for determining the KC130 requirements for fixed-wing aerial refueling missions. The USMC KC130 requirement for broader ranging missions was analyzed in Gates, et al. (1999) and McCarthy (1999).

Aerial refueling is supported entirely through an aerial refueling track (hereafter referred to as a track). Metaphorically speaking, this track is a gas station in the sky. KC130s orbit in a predetermined pattern waiting for refueling customers. KC130s are rotated through the track 24 hours per day, providing customers fuel as needed. KC130 sorties are scheduled to reflect the number of aircraft to be refueled, the time to engage the drogue and receive gas, and the number of drogues. The aerial refueling requirement does not support individual fighter strike sorties.

Using similar assumptions, the aerial refueling requirement was previously analyzed in two Center for Naval Analysis (CNA) reports: "USN/USMC Tanking Requirements" (Cox 1995) and "USMC Organic Tanking Requirements" (Wu and Alexander 1996). These analyses applied queuing theory to determine the number of refueling points (hoses and drogues) required on each refueling track. Queuing theory uses projected average customer (aircraft) arrival rates, average service times (time required to engage the drogue, receive fuel and disengage), and number of servers (drogues), to calculate the expected wait before customers receive service, the average number of customers awaiting service, and the refueling track's capacity utilization.

These analyses used a standard M/M/S multiple server queuing model (Anderson, et al. 1997). Both CNA analyses assumed that five minutes is the maximum average acceptable waiting period and calculated the number of servers required to meet this ceiling.

3 AERIAL REFUELING REQUIREMENTS: QUEUING VERSUS SIMULATION MODEL

Base case aerial refueling assumptions are summarized in Table 1. Refueling assumptions can be grouped into two categories: KC130J performance specifications and aerial refueling demand assumptions. First consider performance specifications. Average customer service times are based on drogue engagement/disengagement times, fuel pumping rates and the quantity of fuel delivered. Base case service times equate to approximately 5 minutes for the average fixed-wing aircraft. In addition, KC130Js require at least three hours on the ground between sorties to refuel the aircraft and refresh and brief the crew. Each KC130J operates for 12 hours per day, including on-ground time between sorties. This analysis also assumes that 90% of all KC130Js are in service (10% are in depot level maintenance) and 80% of the in-service aircraft are capable of completing their mission (72% of all KC130Js are mission capable). Finally, the base case rounds up drogues on-station to an even number to accommodate whole rather than partial KC130s.

Table 1: Base Case Aerial Refueling Assumptions

Value	Characteristic
Performance Specifications	
5	Maximum Expected Wait (Minutes)
5	Service Time Per Customer (Minutes)
2.5%	Drogue/Hose Failure Rate
5	KC130 Sortie Overlap (Minutes)
180	Time On Ground Between Sorties (Minutes)
12	KC130J Operational Hours Per Aircraft Per Day
72%	KC130J Availability
90%	KC130J In-Service Rate
80%	KC130J Mission Capable Rate
Demand Characteristics	
0.338	USMC Arrival Rate Per Minute - West
0.585	USMC Arrival Rate Per Minute - East
2430	Average Fuel Demand (Pounds)

Source: Gates, et al. (1999).

On the demand side, this analysis uses CNA (Cox 1995) customer arrival rates and fuel demands. In the base case scenario, the eastern theater is at peak activity; the west theater is past its peak. Thus, the east theater uses the CNA high scenario customer arrival rates. Customer arrival rates in the West reflect the CNA medium scenario. Refueling demand continues at an even pace 24 hours per day.

The USMC KC130 requirement can be estimated using either queuing theory, as in past studies (Cox 1995; Wu and Alexander 1996), or a simulation model. Unfortunately, queuing models estimate steady-state refueling track performance, but a refueling track may never reach steady-state equilibrium. Departing KC130s briefly remain on-station after their replacements arrive, at least until they finish refueling their current customers, which periodically increases the number of available servers. If the overlap is sufficiently frequent, it may significantly reduce expected waiting time. Conversely, periodic drogue failures reduce the number of servers and increase expected waiting time. This analysis will compare the KC130 requirements estimated by a standard M/M/S queuing model and an aerial refueling track simulated by an ARENA© multi-channel server simulation model. (For a more detailed description of ARENA© simulation models see McCarthy 1999.)

In this comparison, both models assumed two KC130s on-station in the East and one in the West. Both models also used the same probability distributions for customer arrival and service rates. Finally, the initial simulation excluded drogue failures and the overlapping KC130 sorties (i.e., it maintained one KC130 on-station for the entire period). Both models projected average customer waiting time, average number of customers in the queue and system utilization. Given equivalent assumptions, the queuing model and initial simulation model should provide equivalent results, allowing the models results to cross-validate one another.

Two enhancements were added in subsequent simulations to better reflect actual ARCP performance: overlapping KC-130 sorties and drogue failures. To simulate overlapping KC130 sorties, aircraft were rotated through the refueling track on a 45-minute on-station KC130 flight schedule, which will be discussed in detail below. During this rotation, tankers serving customers depart the refueling track after completing the refueling process for their current customers. This overlap effectively doubles refueling track capacity (servers) every 45 minutes. To reflect drogue failures, ARENA© creates an independent chance of failure for each drogue every 45 minutes. With a 2.5% probability, a drogue is seized and blocked for the entire 45-minute period; with a 97.5% probability, the drogue does not fail. In actuality, drogue failures typically occur when customers accidentally dislodge the drogue during the refueling process. Thus, many drogue failures do not last the duration of the tanker's time on-station, as is assumed here.

Table 2 summarizes the aerial refueling track performance results for the queuing model and three simulation scenarios: no overlapping sorties or drogue failures; overlapping sorties but no drogue failures; and

Table 2: Comparative Simulation Results

		East Theater (2 KC130Js)				West Theater (1 KC130J)			
		Queuing Model	Simulation			Queuing Model	Simulation		
			No Overlap No Failure	Overlap & No Failure	Overlap & Failure		No Overlap & No Failure	Overlap & No Failure	Overlap & Failure
Time in Queue	Expected Value	2.2	2.16	1.31	1.46	12.6	12.70	6.38	6.58
	95% C.I.*	-	1.90 - 2.42	1.16 – 1.47	1.27 – 1.85	-	9.16–16.20	5.50 – 7.25	5.47 – 7.70
Customers in Queue	Expected Value	1.3	1.26	0.77	0.86	4.3	4.38	2.19	2.24
	95% C.I.*	-	1.10 – 1.42	0.68 – 0.87	0.75 – 0.98	-	3.10 – 5.66	1.86 – 2.51	1.85 – 2.63
Capacity Utilization	Expected Value	73.1%	72.7%	84.6%	85.7%	84.6%	84.9%	90.6%	90.9%
	95% C.I.*	-	71.4-74.0%	83.3-86.0%	84.5-87.0%	-	82.7-87.0%	88.5-92.7%	89.2-92.6%

*C.I. – Confidence Interval

overlapping sorties with drogue failures. The queuing model results are well within the 95% confidence interval for the simulation model results with no sortie overlap or drogue failures, cross validating both models. The simulation and queuing model results would likely become closer if the simulation period increased beyond 30 days. Table 2 also indicates that sortie overlap significantly reduces expected customer time in the queue and average customers in the queue. Expected time in queue and average customers in the queue both fall by approximately 40% in the east theater; expected time in queue and average customers in the queue both fall by approximately 50% in the west theater. Equally as important, drogue failures only slightly increase expected customer time in the queue and average customers in the queue: approximately 11.5% in the East and 2.5% in the West.

The queuing and simulation model results in Table 2 indicate that the USMC should retain at least two tankers on station in both the eastern and western theaters. Thus, these models suggest similar KC130 requirements with the parameters used here. However, the difference between the queuing and simulation model results is dramatic when the simulation model includes overlapping sorties and drogue failures. This suggests that the KC130 requirements could easily differ with different customer arrival rates or service times. In fact, carefully considering the results in Table 4 indicates that these models might suggest different KC130 requirements even in this case.

To illustrate, consider the eastern theater. The static queuing model indicates that steady-state expected queue time increases to over one hour if one of the four drogues fails. There is almost a 10% probability that at least one of four drogues will fail. If a 10% probability of a queue significantly exceeding five minutes is unacceptable, the queuing results suggest that the USMC should consider maintaining three KC130s on-station in the eastern theater. Unfortunately, this result is misleading. The queuing model result with three servers (one drogue failure) is a steady-state equilibrium; as explained above, the queuing system is unlikely to reach steady-state. Unfortunately, there is no way for the queuing model to depict the temporary drogue failures actually expected on a refueling track, or to weigh these failures against the counterbalancing effects of overlapping KC-130 sorties.

In contrast, drogue failures only last through the current KC130 tanker rotation in the simulation model. Furthermore, simulation shows that overlapping tanker sorties reduce any queue that has formed during the drogue failure. Departing tankers could even temporarily delay their return to base if the queue were unacceptably long and if they had not issued all their available fuel. The simulation model indicates that two KC130s provide sufficient refueling capacity in the East, even with drogue failures. Overlapping tanker sorties and drogue failures will have a larger impact on queuing system performance as capacity utilization increases, because refueling tracks are more likely to have longer queues both when drogues fail and as replacement KC130 sorties arrive.

4 TANKERS ON-STATION (FLOW) VERSUS SORTIE DURATION (STOCK)

Refueling point performance involves flow and stock concerns. The queuing and simulation models just discussed address flow concerns: is there sufficient server capacity to satisfy arriving refueling customers in a timely manner? The USMC must also ensure that sufficient stocks of fuel are delivered to the refueling point to satisfy consumer demand. The stock of fuel delivered per period depends on both the number of KC130s on-station and the frequency with which tankers rotate through the refueling track. Furthermore, these factors are related. For a given customer arrival rate, increasing the KC130s on-station increases the potential time on-station per sortie before each KC130 issues its fuel supply.

Fuel stock considerations require specifying a KC130 flight operations schedule (sortie duration) for both the eastern and western theaters. The flight schedule is limited by the twelve hour operational day and must allow for transit time to and from the theater, one hour pre-flight preparation, two hours post-flight service and maintenance, and at least three hours turnaround time between refueling missions. (These performance characteristics where provided by CNA (Wu and Alexander 1996), Marine Aviation Weapons and Tactics Squadron 1 (MAWTS-1) and at a KC-130J Tanker Requirements meeting held at Naval Air Station, Patuxent River, Maryland, 24 September 1999.) Table 3 summarizes the trade off between time on-station and the number of KC130s required to support one KC130 on-station 24 hours per day, before and after incorporating the 72% KC130J availability. If KC130s remain on-station for 72 minutes, ten mission capable KC130s are required to provide 24-hour coverage. Over a 12-hour period, five aircraft provide continuous coverage by rotating through two sorties per aircraft; five additional aircraft provide continuous coverage for the remaining 12-hour period. With 72% mission capability, this translates into a requirement for 14 KC130s. As the time-on-station decreases from 72 minutes, the aircraft required to provide continuous coverage increases. With the sortie duration considered here, KC130s complete two missions per day in all scenarios and both theaters.

Table 3: On-Station Time Versus the Number of KC130Js Required for Continuous Coverage

Time On-Station (Minutes)	**KC130 Required (24 Hour Coverage)**	
	Without Availability Adjustment	With Availability Adjustment
72	10	14
60	12	17
45	16	22
30	24	34

Using average fuel consumption per customer, the queuing and simulation models indicate that KC130s can remain on station for an average of 100 minutes in the West and 65 minutes in the East, if there are two KC130s on-station in both theaters. This suggests that the USMC consider a 72 minute KC130 flight operations schedule in the West, and a 60 minute flight schedule in the East. Unfortunately, customer arrival rates and fuel demands are probabilistic. If actual consumption exceeds average expected consumption, KC130s will run out of fuel more quickly than expected. The risk of fuel shortages cannot be directly explored using average fuel consumption rates.

Crystal Ball©, a simulation software add-in to Microsoft Excel©, was used to examine how probabilistic fuel demands affect sortie duration. The sortie duration model specifies probability distributions for customer arrival rates and fuel demands. Crystal Ball© uses a Monte Carlo simulation to select parameter values according to the specified probability distributions. Excel© calculates sortie duration for the selected parameter values. (Given the KC130J performance specifications, 30 minutes is the minimum reasonable sortie duration, considering drogue engagement times, fuel pumping rates and the KC130's available fuel supply. This constraint was built into the simulation model.) After conducting the predetermined number of trials, Crystal Ball© reports the simulation results in several formats.

This analysis considered three scenarios: lower variability, base-case and higher variability. The probability distributions for customer arrival rates and fuel demands are more centralized around the mean in the lower variability case, and more spread around the mean in the higher variability case. The range of fuel demands in the higher risk case reflects the range of potential demands in Wu and Alexander (1996). The parameter specifications are summarized in Table 4.

These scenarios can be interpreted in at least two different ways. They can represent three possible descriptions for the relevant customer demand variability, only one of which describes the actual situation. Presenting three scenarios indicates the impact variability has on

Table 4: Crystal Ball Sortie Duration Simulation Assumptions

Parameter	Distribution	Theater	Mean	Scenario	Minimum	Maximum
Customer Arrival Rate (Per Hour)	Poisson	East	35.1	Lower Risk	0	48
				Base Case	0	Infinite
				Higher Risk	0	Infinite
Customer Arrival Rate (Per Hour)	Poisson	West	20.3	Lower Risk	0	30
				Base Case	0	Infinite
				Higher Risk	0	Infinite
Fuel Demand (Pounds Per Customer)	Triangular	Both	2430	Lower Risk	1500	3500
				Base Case	1000	4500
				Higher Risk	1000	6000

KC130 requirements and refueling track performance. Alternatively, the three scenarios could represent potential MTWs (e.g., each scenario represents a potential theater, where theaters differ in fixed-wing mission profiles, distance from base to theater, etc.). Here, the USMC would have to consider all three scenarios and their associated probabilities to determine KC130 requirements and refueling track performance. This analysis considers the first perspective.

The Monte Carlo simulation involved 10,000 trials, representing 10,000 KC130 sorties. With two KC130s on-station in the East and the base-case customer arrival and fuel demand assumptions; Crystal Ball© forecasts a 65.34 minute average sortie duration, consistent with the queuing results (65 minutes). However, sortie duration is 60 minutes or longer in only 53.95% of the trials (Figure 1). If USMC implements a 60 minute KC130 rotation schedule, both tankers will issue their fuel supply in less than 60 minutes in just over 46% of the tanker sorties. If the USMC implements a 45 minute KC130 rotation schedule, both tankers will issue all their fuel in less than 45 minutes in approximately 13% of the Tanker sorties. Aerial refueling customers would be left without fuel in these cases. In the West base case with 2 KC130s on-station, both tankers run out of fuel in approximately 13% of the sorties with a 72-minute KC130 rotation schedule, and approximately 3% of the time with a 60 minute rotation.

Stock considerations highlight another point. Maintaining an additional KC130 on-station increases sortie duration. Increasing sortie duration can compensate for the additional KC130 on-station, particularly for shorter sorties. As sortie duration increases from 30 to 45 minutes, the KC130s required to maintain one aircraft on-station decreases from 34 to 22 (Table 3). Maintaining three tankers on-station for 45 minutes requires fewer KC130s than maintaining two on-station for 30 minutes (i.e., $3*22 = 66 < 2*34 = 68$). This tradeoff should be considered in determining the minimum KC130 requirement.

Table 5 illustrates the interaction of flow and stock considerations. Flow considerations require maintaining at least two KC130s on station on both the East and West. Stock considerations dictate short sortie duration in several scenarios. As a result, the KC130 requirement is lower maintaining three KC130s on-station in the East Base Case, East Higher Risk Case, and West Higher Risk Case.

Table 5: KC130 Requirement to Meet Server capacity (Flow) and Fuel Supply (Stock)

Theater	Scenario	KC130s On-Station	Sortie Duration	KC130 Require-ment
East	Limited Risk	2	45	44
		3	60	51
	Base Case	2	30	68
		3	60	51
	Higher Risk	2	30	68
		3	45	66
West	Limited Risk	2	72	28
		3	72	42
	Base Case	2	60	34
		3	72	42
	Higher Risk	2	45	44
		3	72	42

5 KC130 AERIAL REFUELING COST-RISK TRADEOFF

The preceding discussion indicates that there are at least two risks inherent in determining the KC130 fixed-wing aerial refueling requirement: flow and stock risks. However, reducing flow and stock risks by deploying additional KC130s increases KC130 program costs. Accommodating higher KC130 fleet costs requires

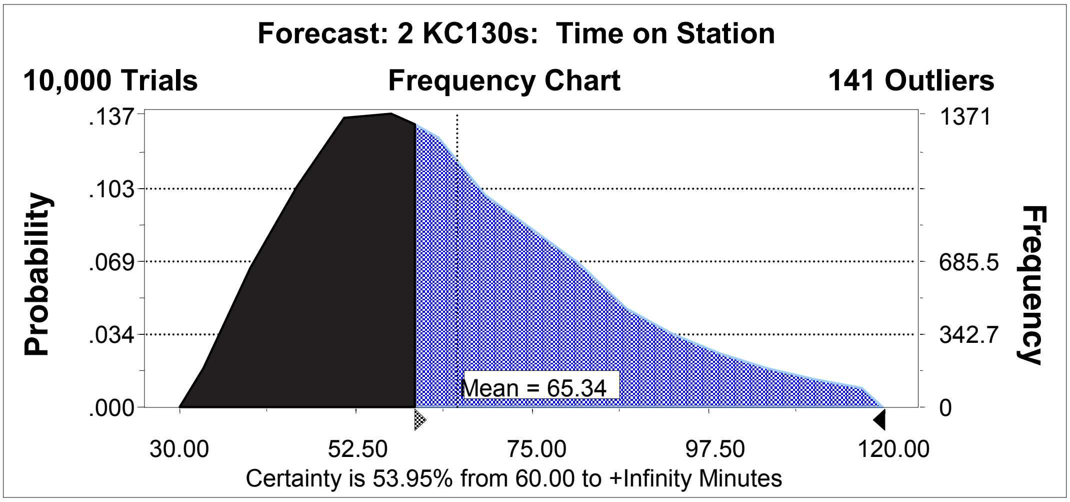

Figure 1: Sortie Duration Simulation Results - East Theater, Base Case, Two KC-130s On-Station

increasing the program budget. Thus, it is important to consider the tradeoffs between refueling track performance and the KC130J requirement and program costs.

As estimated elsewhere (Gates, et al. 1999), the present value lifecycle cost for one KC130J is \$119.2M (i.e., the cost to purchase and maintain one KC130J over its life time (40 years), including acquisition, maintenance and support, expected up-grades, and salvage value or disposal). (McCarthy 1999, explores the implications using Crystal Ball© to estimate probabilistic lifecycle costs.) To illustrate the tradeoff between refueling track performance and cost, the minimum number of KC130s required to ensure a given probability of completing scheduled sorties can be determined for different probabilities of success. Costs can be calculated for each KC130 requirement.

Figure 2 illustrates the relationship between probability of completing the scheduled sortie and both the KC130 requirement (left axis) and program cost (right axis) in Millions of 1999 dollars. (This analysis could use Crystal Ball© to construct a probabilistic LCC model (see M^{c}Carthy 1999). This would estimate a cost range for each KC130 requirement. The USMC could then examine the tradeoff between probability of completing scheduled sorties and expected cost, as reported here, along with worst and best case cost estimates.) The data in Figure 2 can help determine the USMC fixed-wing aerial refueling requirement. Suppose these scenarios represent three possible descriptions for the relevant customer demand variability, only one of which describes the actual situation. If the limited variability case is the relevant scenario, the tradeoff between cost and probability of completing scheduled sorties begins increasing after this probability reaches 85% (70 KC130s). If the USMC increases the KC130 requirement from 70 to 72 aircraft, they can increase the probability of successful sortie completion from 85% to 95%. To increase this probability to 100%, the KC130 requirement increases from 72 to 85, which represents an additional \$1,550M in LCC.

In the base-case, costs begin increasing significantly once the probability of successful sortie completion reaches 85%; costs increase significantly throughout the entire range in the higher variability scenario. The USMC may decide to settle for a lower probability of successful sortie completion if these are the relevant scenarios.

6 SUMMARY AND CONCLUSIONS

Static queuing models, which have been used to estimate USMC KC130 aerial refueling requirements, do not incorporate the full complexity of refueling track performance. Queuing models don't account for either the impact of overlapping KC130 sorties and drogue failures on refueling track performance, or the impact of variable customer arrival rates and fuel demands on sortie duration. The first issue involves the ability to service aerial refueling customers in a timely manner (flow); the second issue involves the supply of fuel available for refueling customers (stock). Two simulation models were introduced to address these issues. An ARENA© simulation model was used to analyze how overlapping KC130 sorties and drogue failures affect refueling track performance (expected time in the queue, average customers in the queue, and refueling track capacity utilization). A Crystal Ball© simulation model was introduced to assess the impact of sortie duration on refueling track performance and the KC130 requirement.

The ARENA© simulation model indicated that maintaining two KC130s on-station provided a sufficient flow of fuel in the east theater, vice the three KC130s suggested by the queuing model (considering drogue

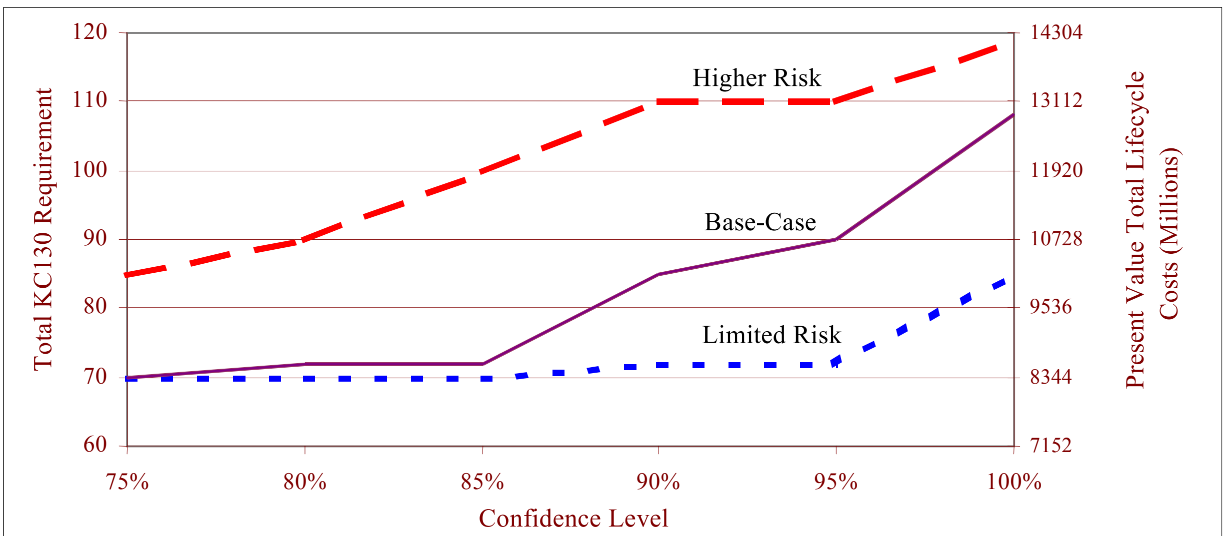

Figure 2: KC130 Requirement, One Generation Lifecycle Cost and the Probability of Completing Scheduled Sorties

failures). Both models maintained two KC130s on-station in the West. The Crystal Ball© simulation model illustrated a tradeoff between sortie duration, KC130s on-station and the probability of completing the scheduled sortie before issuing all available fuel. In some instances, it is efficient to maintain more than the required KC130s on-station. This increases sortie duration and actually reduces the total KC130 requirement. More aircraft are required in each sortie, but fewer aircraft are required to provide the necessary rotational base. The results of this simulation model were used to generate tradeoffs between the KC130 requirement and the probability of providing a sufficient fuel supply at all times. Depending on both the refueling track performance desired and the variability of customer arrival rates and fuel demand, the KC130 fixed-wing aerial refueling requirement ranges between 70 and 120. Ultimately, the USMC must determine the appropriate balance between costs and performance. However, this topic is beyond the scope of this paper.

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